Evaluation of Different Airflow Sensors at the WIPP Facility

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ABSTRACT

The Waste Isolation Pilot Plant (WIPP) is an U.S. Department of Energy underground disposal facility designed to permanently and safely isolate U.S. defense-generated transuranic radioactive waste. The underground ventilation system is engineered to minimize the release of radioactive contamination to the environment in the event of an accident.

During 1994 an extensive ventilation remote monitoring and control system was installed. It consists of fifteen air velocity sensors, eight differential pressure stations, automated control features on key underground air regulators, and eight psychrometric stations.

The airflow monitoring component of the system has been a problem since the original installation. Due to the WIPP's variable airflow capabilities, the air velocity sensors required extensive and time-consuming re-calibration to make the sensors read out volumetric flow, rather than the point or line values, which they were factory calibrated for. Problems with the hardware made the process difficult. Furthermore, once re-calibrated the durability and reliability of the units were inconsistent, and often unacceptable.

Two new types of airflow sensors were tested; one or both of which will ultimately replace the old units. The tested sensors were an ultrasonic-type device (FloSonic), and a warm body, mass flow unit (Airboss*200W) (a re-engineered version of the previous units). Recommendations were made regarding which type of sensor to install at specific locations. These decisions were based on the conditions at each sensor location and the relative strengths of the two sensor types. Installation, field calibration methodology, test procedures, main results and recommendations are discussed.

KEYWORDS

Sensor, AirBoss, FloSonic, WIPP, Airflow, Monitor, Equipment, and Instrumentation.

INTRODUCTION

The Waste Isolation Pilot Plant (WIPP) is designed to permanently isolate from the biosphere transuranic waste left from the research and production of nuclear weapons. The WIPP is located in southeastern New Mexico, 43 kilometers (26 miles) east of Carlsbad. Project facilities include disposal rooms excavated in an ancient (approx. 250 million years old) stable salt formation 660 m (2,150 ft) underground. Transuranic waste consists of clothing, tools, rags, and other items contaminated with trace amounts of radioactive elements, mostly plutonium.

The underground ventilation system is engineered to perform two distinct functions. First, it fulfills normal mine ventilation requirements in compliance with all state and federal mine regulations. Second, it prevents the uncontrolled release of radioactive contaminants from the facility. Although a nuclear radiation release in the facility is considered very unlikely, the ventilation system incor-porates many special features to reduce or prevent the spread of contamination.

Description of the Ventilation System

The underground facility is accessed and ventilated through four vertical shafts, three of which act as air intakes and the fourth is the common exhaust. The three intake shafts at the WIPP are the Waste Handling Shaft (WS), Salt Handling Shaft (SHS), and Air Intake Shaft (AIS). The Exhaust Shaft (ES) is the only return airway. During normal operation most of the intake air flows underground through the AIS. The SHS, which also provides personnel and material access, is used for the removal of the mined salt and as a secondary intake shaft. The WS is equipped with an enclosed head-frame and is used for lowering the waste to the repository horizon. This shaft also serves as the air intake for the WS station and provides access for personnel and materials to the repository horizon. The WS air is isolated from the rest of the repository and is routed directly to the ES after ventilating the shaft station area.

Underground ventilation at the WIPP is accomplished with four main circuits called the north area, mining area, waste disposal area, and the WS station. In order to minimize occupational exposure of underground personnel to radiation and radioactive materials, the facility is designed and constructed based on the ALARA (As Low As Reasonably Achievable) concept. This concept resulted in a design where the nuclear waste transportation and disposal areas are separated from the mining and non-radioactive material areas. The ventilation system is also designed such that air leaks from the mining and north areas into the waste disposal areas. Furthermore, radiation detectors are strategically located underground, and an exhaust filtration system on the surface is available to minimize the possible release of radioactive materials to the environment in the event of an accident.

Ventilation through the facility is supplied by running either one or two of three available 450 kW (600 hp) centrifugal main fans. During concurrent mining and waste disposal operations two of the fans operate in parallel to provide 230 m^3/s (490,000 cfm). When either mining or waste disposal is not taking place, the ventilation demand is decreased, and only one main fan is operated, resulting in an airflow of 140 m^3/s (300,000 cfm). In the unlikely event of an underground radioactive materials release, the ventilation system is shifted to "Filtration Mode", where the airflow is reduced to 28 m^3/s (60,000 cfm). This airflow is achieved by turning off the main fans, and starting one of three 175 kW (235 hp) centrifugal stand-by filtration fans. A series of isolation dampers divert the air through the filtration system, which consists of a series of High Efficiency Particulate Air (HEPA) filters.

Remote Monitoring and Control Capabilities

A high degree of monitoring has been incorporated into the design of the underground ventilation system. Some mandatory capabilities, which are required to comply with and document facility operational readiness standards, include fan status, bulkhead status, and key differential pressures. In addition, two elective remote monitoring systems are in place to collect (non-compliance) data on the status of the underground ventilation system. The Underground Ventilation Remote Monitoring and Control System (UVRMCS) collects data on airflow, differential pressure, and key regulator positions. The mine weather stations collect psychrometric data. The data are eventually routed to the Central Monitoring Room (CMR) through the site-wide Central Monitoring System (CMS). Details of the WIPP remote monitoring and modeling capabilities have been published in a series of papers (Strever *et al.*, 1995, McDaniel *et al.*, 1996, McDaniel, 1997).

The availability of real-time data from the remote monitoring system provides for a variety of beneficial uses. The data collected can then be used in; 1) Natural Ventilation Pressure (NVP) calculations, 2) WIPPVENT, an interactive mine ventilation simulation software program, and 3) psychrometric calculations.

PROBLEMS WITH AIRFLOW SENSORS

WIPP Mine Engineering identified certain problems with the old underground airflow sensors. These sensors comprise one component of the UVRMCS. The existing warm body sensors (Airboss*200, purchased from Rel-Tek Corporation) have been difficult to re-calibrate to WIPP's variable airflow requirements, and the output signal has had a tendency to "stray" immediately following re-calibration. The unreliability and lack of repeatability of these instruments in this application has hampered the continued development and use of the UVRMCS. For this reason WIPP developed a plan to install and test two new types of airflow sensors.

During the initial installation of the Airboss*200 units in 1994, problems were noted pertaining to calibration accuracy, complexity and consistency (Strever, *et al.*, 1995). In March 1997, a site-wide re-calibration was attempted. The test criteria for the re-calibration of the airflow sensors required each to report the mean air velocity to within 10% of measured (using a calibrated vane anemometer and full-section traverse) throughout the entire operating range of velocities for the specific area. To pass this criterion, it was necessary to replace approximately 50% of the sensors. This was a time consuming and expensive process. There appeared to be no consistent problem with the Airboss*200 units, therefore it was necessary to evaluate each sensor individually. Some of the problems encountered were:

- The zero point on the unit (corresponding to no airflow) would drift.
- One of the sensors did not allow either uploading or downloading of calibration curves.
- The newer sensors (purchased in 1997) were found to react strangely to varying airflow. The display would not smoothly change to reflect airflow adjustments, but would freeze on a value and then "jump-up" in at least 100 ft/min increments. This caused a problem with some sensors that would "stick" on a reading, even though the actual airflow was significantly lower or higher than that value. The manufacturer attributed this to inherent discontinuities between the field data and the factory calibration table, which disrupted the "hill-climbing" interpolation algorithms used.
- Field re-calibration of the units was very tedious. Two different methods were used to adjust the factory calibration curves to report *mean* airway velocities (which may differ significantly to the spot reading at the sensor). One method was to change airflow through the drift and record a series of indicated and measured (anemometer) airflows. A curve was then fitted to the data (using a suitable software program). The new cali-

bration was downloaded to the sensor, and the airflows rechecked (and invariably the calibration curve needed to be finely adjusted again). The other method was to start at the highest airflow, and use the PicoPort (PSION instrument interface device) to change the relevant calibration points until the display recorded correctly. Gradually the airflow was reduced, and the calibration points were adjusted throughout the operating range. However, for some cases the velocity profile in the airway was very irregular, and the corrections to the calibration data were large. In these cases it was almost impossible to calibrate the sensors to provide accurate readings over the entire airflow range. This problem is not limited to the Airboss*200 units, but is encountered with any spot-measuring device.

A number of the Airboss*200 units would not fully accept download changes until the unit had been reset (by turning off the power).

Many of the difficulties encountered with the Airboss*200 in this application can be attributed to the fact that the WIPP has unique ventilation capabilities, henceforth, possibly unique requirements for instru-mentation. The Airboss*200 was originally selected partly because it had a proven record in the field. Westinghouse recognized that the manufacturer's engineers were approaching the calibration issue from a completely different perspective than that used at the WIPP. At the testing laboratory, the airflow sensor is mounted in the *center* of a wind tunnel and a specific airflow is set (e.g. 1.0 m/s {200 ft/min}), then the probe calibration of the unit is changed to correspond to the 1.0 m/s (200 ft/min) output point. During a typical field calibration the engineer/ technician does not have the capability to cycle up and down the curve to settle on exact airflow values. The WIPP system required that a calibration curve be field fit under conditions of widely varying airflow velocities and profiles. The results of the calibration effort were conveyed to the manufacturer, and the unit was redesigned to try to address the various limitations of the original sensor.

Outline of Test

Two different types of airflow sensors were procured and tested in the WIPP underground over a four-month trial period. These were:

1. Redesigned Airboss*200W unit available from Rel-Tek Corporation. The manufacturer developed this new sensor with considerable input from project and subcontractor personnel. The final product incor-porated new features, including greatly improved software (easy to use, with uploading/downloading capabilities), improved user interface (with an RS-232 port on the digital display unit), and an improved startup sequence.
2. FloSonic unit available from El-Equip. This type of sensor was not available when the UVRMCS was installed in 1994. It is a microprocessor-based ultrasonic airflow sensor. Unlike the warm-body sensors, this instrument requires minimal calibration to obtain representative mean velocity values for the mine airway.

The following test procedure was adopted:

- Remove three existing Airboss*200 sensors from the facility.
- With the assistance of a manufacturer's technician, install and calibrate new Airboss*200W units at three of the fifteen original airflow stations. Locations with a variety of airflow characteristics were chosen.
- Install a FloSonic unit in an area of the mine that typically experiences high airflows. After initial test-ing, move the FloSonic unit to a location with low velocity conditions.
- Two distinctly different airflows will be measured at each sensor location (using a calibrated vane anemometer and a full traverse method). These measurements will be conducted approximately once every two weeks, and the measured air velocities will be compared against the values indicated on the local displays. Adjustments to the underground regulators and changes to the main fan configuration will be used to obtain these differing levels of airflow.
- The absolute deviation for the measured airflows shall be determined at each sensor. A PASS/FAIL criterion was developed for the initial installation of the remote monitoring system based on 10% of the measured airflow value. This criterion was not enforced for the sensor test; however, it was recognized that the selected unit would have to be capable of achieving this accuracy when permanently installed in the facility.

Installation and Calibration of Sensors

The Airboss*200W sensors were calibrated using the following procedure:

1. Adjust the ventilation system to provide multiple airflow values within the normal operating range of each sensor. The measured mean air velocity and indicated velocity (read off the local display) are determined for each different quantity.
2. Develop a graph of *measured* airflow against the indicated airflow using an Excel spreadsheet.
3. Fit a curve through the points, and determine the equation of this trend. Using this relationship, develop a new "calibration" curve for the sensor (within the range of measured velocities). This curve is uploaded to the sensor.
4. Conduct at least two spot checks immediately following the calibration procedure to ensure that the new calibration curve is acceptable.

The installation of the FloSonic unit was a relatively simple procedure. The sensor consists of a control module and two transducers. The control module is packaged in a NEMA enclosure. The transducers are completely sealed, which allows them to be used in harsh environments.

Figure 1 is a sketch of a typical installation for the FloSonic transducers. The probes are spaced at a linear distance (a) along the airway. The accuracy of the instrument depends on three factors, which are:

1. Distance between the two transducers (d).
2. Angle of the transducers to the airflow axis.
3. Air velocity.

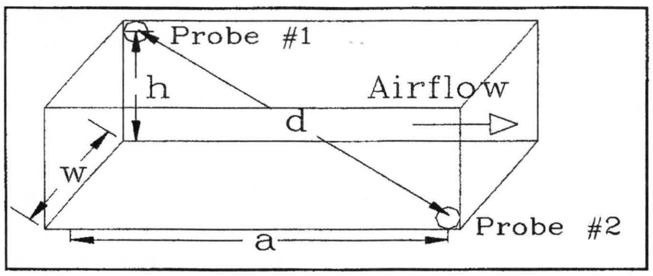

Figure 1. FloSonic installation.

There exists an optimum distance between the two transducers (d) of about 15 m (49 ft) (obtained from the manufacturer). Hence, if the height (h) and width (w) of the entry are known, the linear distance (a) can be evaluated for any proposed sensor location. For the test, the transducers and the control module were bolted to the ribs. It was necessary to install a protective shield around the floor-mounted transducer to prevent it from being knocked by personnel or equipment. The two sensors were aligned using a laser-pointer device supplied by the manufacturer. Minimal field calibration procedure was required for the ultrasonic unit. The only inputs required were d, a, and the airway mean cross-sectional area. Input was via a Windows-based software program, which was loaded onto a laptop computer.

Results From the Field Measurements

Testing of the sensors was conducted over a four-month period. These tests consisted of measuring the mean air velocity at each station, and comparing the measured values with the locally indicated readings. To simplify the viewing of the data, bar charts showing the deviations associated with each measured value are presented in the following figures. The deviation is given as a percentage of the measured velocity.

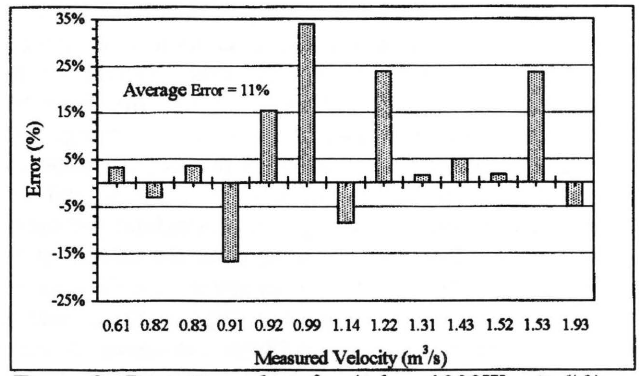

*Figure 2. Deviation values for Airboss*200W unit (#1).*

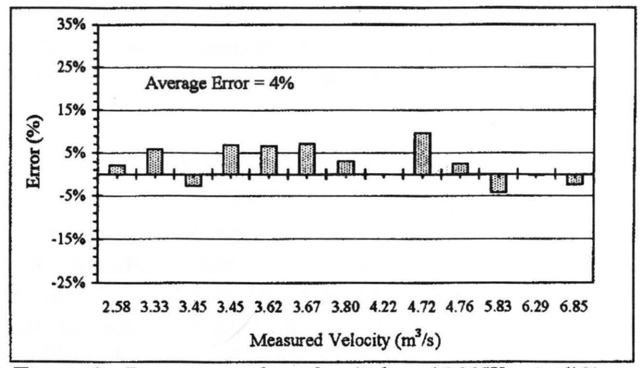

*Figure 3. Deviation values for Airboss*200W unit (#2).*

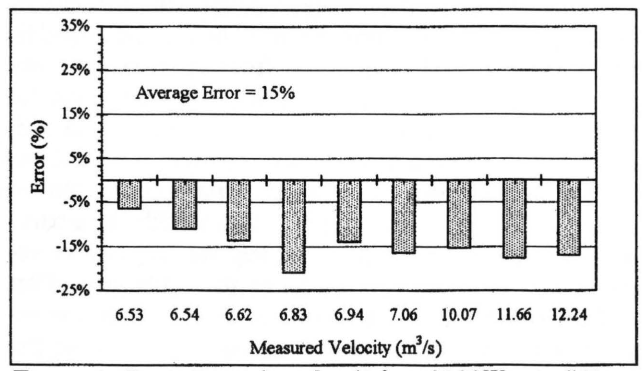

*Figure 4. Deviation values for Airboss*200W unit (#3).*

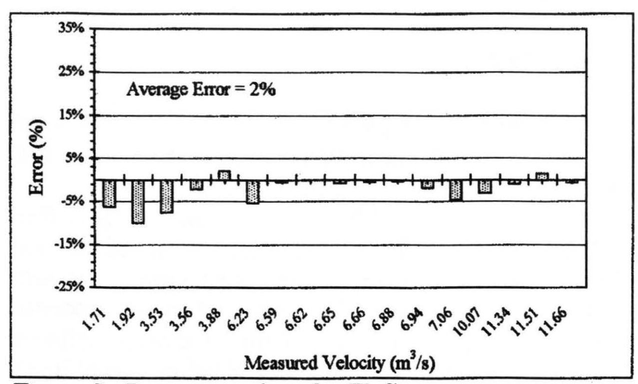

Figure 5. Deviation values for FloSonic sensor.

DISCUSSION OF RESULTS

Airboss*200W Results

The average deviation for the Airboss*200W unit #1 was determined to be 11%. This deviation is above the limit of the system FAIL criterion, which was set at 10%. However, an examination of Figure 5 shows that the average deviation is biased by three readings in particular, which have deviations greater than 20%. If these values are omitted, the average deviation drops to a respectable 6%. It may be justified to exclude these values as erroneous readings, which could be caused by measurement error or a failure to let the sensor display settle on the correct reading. However, if the other two values showing a high deviation are examined (measured velocities of 0.91 m^3/s {180 ft/min} and 0.92 m^3/s {182 ft/min}) an unexplained fact is revealed. It would be expected that the Airboss*200W unit would read either consistently high or low for the same measured velocity. The data show that the unit was reading 0.15 m^3/s (30 ft/min) *lower* than 0.91 m^3/s (180 ft/min) on one day; however, approximately one month later the unit was reading 0.14 m^3/s (28 ft/min) *higher* than 0.92 m^3/s (182 ft/min). This suggests that the sensor was experiencing considerable fluctuations. These fluctuations were not apparent from a short-term visual observation of the display, but were identified over the two-month measurement period. The tested velocity range was 0.61-1.93 m^3/s (121-379 ft/min), which corresponds to the maximum and minimum expected velocities in the airway. The range of values over which the #1 sensor was calibrated was 0.73-2.13 m^3/s (143-419 ft/min).

Sensor #2 was the only Airboss*200W unit that passed on every reading. The sensor was tested over the range of 2.58-6.85 m^3/s (507-1,349 ft/min) and was calibrated over the range of 2.52-4.80 m^3/s (497-945 ft/min). The average deviation for this sensor was 4%, which is considered very good. The most obvious difference between sensors#1 and #2 is that the #2 sensor was neither calibrated nor tested for the low velocity range of 0-2.54 m^3/s (0-500 ft/min). Both calibration and testing are considerably more difficult for the lower velocities, where the air velocity profile appears to be less uniform. Another difference is that from initial installation (prior to re-calibration), the #2 sensor was reporting velocities that were relatively close to those that were measured. This is apparent from examination of Table 1, which shows the data collected from the sensors *prior* to re-calibration.

For each sensor it can be seen that the deviation decreases as the measured air velocity increases (Table 1). This suggests that the airflow becomes more uniform across the entry as the velocity increases. This results in the spot reading being more representative of the mean velocity at the higher airflows. The original calibration curve should not have much impact on the results, because an entirely new curve is developed. However, it appears that in certain cases a secondary calibration may be necessary to ensure the required accuracy.

Due to the high air velocities experienced in the airway with the #3 sensor, the instrument was fitted with a reduction cowling on the discharge side. This device is supplied by the manufacturer and is designed to permit operation of the instrument above the normal limit of 10.16 m^3/s (2,000 ft/min). The sensor is a mass-flow type unit that measures the cooling effect of air passing over a heated probe (changes in resistance are proportional to the mass of air across the probe). However, when the air velocity reaches about 9.14 m^3/s (1,800 ft/min) the incremental cooling with increasing velocity becomes very small, and the sensitivity of the sensor may be compromised. The presence of this cowling may have affected the accuracy of the #3 sensor (average deviation was 15%).

Table 1. Initial data obtained from the #1 and #2 Airboss*200W sensors.

Airboss Sensor #1

Measured Airflow (m^3/s)	Indicated Airflow (m^3/s)	Difference (m^3/s)	Difference (%)
0.73	0.51	0.22	30%
0.87	0.61	0.26	30%
1.19	0.91	0.28	23%
1.52	1.14	0.38	25%
1.91	1.68	0.23	12%
2.13	1.93	0.20	9%

Airboss Sensor #2

Measured Airflow (m^3/s)	Indicated Airflow (m^3/s)	Difference (m^3/s)	Difference (%)
2.52	2.12	0.41	16%
3.22	2.49	0.73	23%
3.28	2.60	0.68	21%
3.83	3.30	0.52	14%
3.94	3.51	0.44	11%
4.55	4.15	0.40	9%
4.80	4.42	0.38	8%

Following the completion of the test, another potential reason for the poor performance of the #3 sensor was identified. The new calibration curve for the #3 sensor had been developed over the range of 0-20.32 m^3/s (0-4,000 ft/min), rather than the operable range of 0-12.7 m^3/s (0-2,500 ft/min). Because the calibration curve is limited to 13 points, and two of these points are accounted for with the zero and maximum values, it is important to limit the curve to just the operable range (better definition of the curve resulting in improved interpolation between data points).

FloSonic Results

Figure 5 reveals that the ultrasonic airflow sensor recorded acceptable results over the entire 1.71-11.66 m^3/s (336-2,295 ft/min) test range. Furthermore, the average deviation of 2% is less than half of that reported by the best Airboss*200 unit (#2). The highest deviations were found in the lower velocity range, where below 3.56 m^3/s (700 ft/min) the average deviation approached 6.5% for five readings. Although this meets the compliance criteria, the sensor was moved to a large airway with low velocities and re-checked. The results from this test are shown on Figure 6.

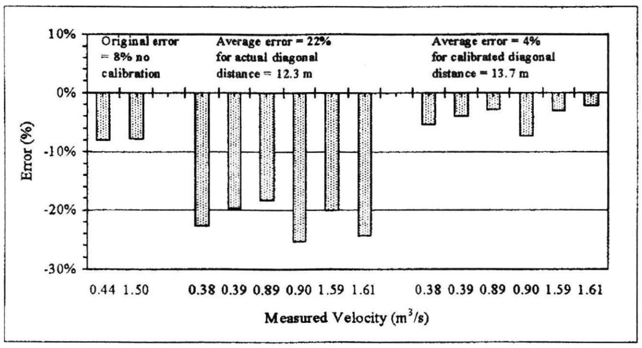

Figure 6. Deviation values for FloSonic located in low air velocity site.

When the sensor was moved to the new location, a number of problems were encountered. When originally installed, it was difficult to maintain a strong signal between the two sensor heads at a 14 m (46 ft) diagonal distance. Preliminary results obtained for this diagonal distance showed an average deviation of 8% for two low velocities. However, the sensor output would consistently "lock-up" and give very slow response times to variations in airflow. To mitigate this problem the diagonal distance between the sensors was shortened to 12.3 m (40.5 ft). At this distance the signal was very strong and the sensor reacted quickly to changes in airflow; however, the deviation between measured airflow and sensor output increased to an average and relatively consistent 22%. To verify that the measured air velocities were accurate, two different calibrated anemometers were used. No difference in the measured air velocity was noted between the two anemometers. The measured air velocity was consistently higher than the sensor indicated air velocity.

Because the deviation was relatively uniform, it was decided to re-evaluate the sensor sensitivity by changing the geometric input parameters via the software. After several iterations, it was discovered that changing the diagonal distance to 13.7 m (45 ft) (even though the actual distance was 12.3 m (40.5 ft)) significantly reduced the deviation for each measured airflow to an average of 4%. To determine why this was occurring, several telephone conferences were held with the manufacturer. The manufacturer verified the sensor wiring and software, but was unable to say why the sensor worked with a modified diagonal distance in the low airflow regimes. Manufacturer's technicians are continuing to work on this finding, but it appears that with minimal effort the sensors can be "calibrated" to operate in all ranges of drift size and air velocities. Power outages posed no problem for the FloSonic, which reset itself when power was restored.

COMPARISON OF TEST RESULTS

The new Airboss*200W units are far superior to the original units used at the WIPP Facility. Given these improvements, the Airboss*200W should provide even better service for those applications that do not have the unique requirements found at the WIPP site. The following advantages were noted with the new units:

1. Easier interaction via a laptop, rather than a PSION Organizer (as previously required).
2. Ability to program the sensor through the digital display box, rather than the actual suspended unit.
3. Considerably better durability (no faults occurred during the testing phase).
4. Not affected by power outages, and reset without any problems.
5. Improved manipulation of the calibration curve matrix, including the ability to develop entirely new curves from measured data.
6. More steady calibration, although "straying" was noted with the #1 sensor near the end of the test phase.
7. Much more stable output, which did not suffer the short-term fluctuations that were noted with the previous Airboss*200 units.
8. Improved zero and span reset via buttons. The old units had to be covered to verify or reset the zero signal to 4 mA. This procedure is no longer necessary.
9. MSHA classified G, H, and DL for use in hazardous methane areas. The FloSonic is not.

Certain problems continue to complicate the application of the Airboss*200W units at WIPP (which may not apply to other field installation depending on circumstances). The main problem is that the field re-calibration procedure remains fairly cumbersome. Furthermore, it is likely that for some of the sensors a secondary calibration will be required to reduce the deviation below 10%. This will result in additional man-hours being necessary to calibrate certain sensors. However, it is anticipated that once the units are properly adjusted, then a full annual re-calibration of each sensor will not be required (which was necessary with the old sensors due to the lack of repeatability of the unit).

The FloSonic unit is typically more accurate, once the diagonal distance parameter is determined, than the Airboss*200W unit. Problems with the FloSonic sensor include; 1) requires a considerable length of unobstructed entry for installation, and 2) although the adjustment of the diagonal distance in the software appears to solve the large deviation problem, the reason for the fix is unknown.

The strengths and weaknesses of both sensors are outlined in Table 2. When applicable, the airflow sensor that excels has been highlighted for each category.

Recommendations

The final results indicate that the FloSonic unit is the superior sensor for the WIPP. This may or may not be true for other installations depending on needs and circumstances. The Airboss*200W unit measures velocity at a specific point in the entry, which is often not representative of the mean air velocity. Subsequently extensive recalibration was usually required for this type of sensor. Conversely, the FloSonic unit takes a mean reading across the drift, which compares closely to a manual air velocity taken by traversing across the entry using a vane anemometer. The FloSonic unit may require some calibration at each flow station to ensure accurate readings. This appears to be possible by altering the diagonal distance between probes in the sensor software.

Test results indicate that the FloSonic unit can provide accurate results in all expected velocity ranges at the WIPP. To enhance the remote monitoring system, it was recommended that the UVRMCS be upgraded to incorporate FloSonic airflow sensors. The FloSonic will be installed at locations where the required accuracy and operating range or installation conditions dictate its use. The Airboss*200W will be installed in those locations where the use of the FloSonic sensor is not applicable. Switching to the two new types of airflow sensors should provide WIPP with the accuracy that is required to fully use all aspects of the UVRMCS.

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Table 2. Strengths and weaknesses of Airboss*200W and FloSonic units.

Category	Airboss*200W	FloSonic
Ease of Calibration	Extensive and time consuming	***Minor calibration to diagonal distance required***
Accuracy	Acceptable within small calibrated range	***Good over entire range***
Cost	***$2,000 for each new sensor***	$2,500 for each new sensor
Ease of Installation	Average - Requires mounting bracket on roof. May require leveling jig to obtain proper alignment.	***Easy. Unit may be bolted to ribs without any special bracket. Alignment is important but not critical. Alignment obtained by use of a laser pointer.***
Durability & Reliability	Improved over previous sensor	Insufficient data – No problems to date
Impact of Dust	Periodic cleaning of probes	***No effect***
Software	***Good. Easy to manipulate and communicate.***	Can be difficult to download. User has no clear indication that communications were successful.
Particular Suitability	• Short sections of entry, where FloSonic cannot fit. • Areas with mid-range air velocities, where many points can be measured over a relatively small span.	• Longer sections of unobstructed entry. • High velocities. • Areas with a wide span of air velocities - i.e. large operating range.